



Magnetotransport Measurements in Advanced Materials

Magnetotransport measurements, including magnetoresistance and Hall Effect, are important tools for characterizing commercially significant materials as well as new materials in research. To thoroughly characterize magnetotransport, the researcher needs to control several experimental variables. These include

magnetic field (magnitude and direction), temperature and sample orientation. In addition, it is common to produce a large number of samples (perhaps with different characteristics) on a single wafer. Although traditional resistance measurements with four in-line probes are still very useful, new applications require more flexible probe placement. Examples of different measurement geometries include measurements made with the current perpendicular to the plane or the current in plane. Additional concerns when measuring transport properties include the effect of self heating on the measurement and even the lifetime of the sample. In this article we outline several magnetotransport measurement techniques and methods to improve measurement quality and speed.

Historic Background

Magnetoresistance is broadly defined as a change in the resistivity of a material when the material is subjected to a magnetic field. The magnetoresistance of nickel and iron was first reported 150 years ago by William Thomas (Lord Kelvin). Since then magnetoresistance has been observed in a wide range of materials, from metals to semiconductors and quantum structures. With the advent of the quantum theory of materials, it is understood that magnetoresistance is a method to explore the structure of the Fermi surface of materials. Magnetoresistive devices can also be used as magnetic sensors. The anisotropic magnetoresistance read head was a staple of the hard drive industry until the mid-1990s. In 1989 the giant magnetoresistance effect was first reported. The recent Noble prize awarded to Albert Fert and Peter Grunberg is a testimony to the significance of this discovery.

Magnetoresistance is often measured using four probes in a fixed geometry. Two of the leads are connected to a current source and the other two leads are connected to a voltmeter. If the current flow in the material is two dimensional, and the dimensions of the sample and probes are known, there are well known relationships between the current, the voltage and the resistivity. In addition, there are good approximations to estimate the systematic errors introduced by the measurement methods.

The van der Pauw method is specifically designed to measure two dimensional samples where it is not necessary to know the physical dimensions of the sample. The van der Pauw equation is used to calculate the resistivity from resistance measurement. This method assumes that there are four point contacts on the edge of the sample. In addition to magnetoresistance effects (defined as electric field parallel to the current), there is the Hall effect and planar Hall effect. The Hall effect is a voltage across a material proportional to the

magnetic field perpendicular to the current. For the planar Hall effect, the field is in the plane of the sample, rather than perpendicular.

Measurements of Magnetic Tunnel Junctions

Research using magnetoresistance in quantum structures often uses measurement configurations very different from the classical four point probes in a line. A typical configuration is two metals separated by an oxide insulator. In these devices the current tunnels through an insulating layer to get from contact to contact (Figure 1). This tunneling is a quantum mechanical effect; no current would flow through the device if it behaved according to classical physics.

If the metals in the device are ferromagnetic materials, the resistance of the device is higher when the magnetic layers are magnetized opposite to each other (anti-parallel). The tunneling magnetic ratio (TMR) is the ratio of the resistance when the layers are magnetized anti-parallel to the resistance when the layers are magnetized parallel to each other. The TMR depends on the materials used in the device, the temperature of the device and the thickness of the insulating layer. A typical sample is prepared with many devices on one substrate, and the thickness of the insulator varies along the length of the sample.

To measure the TMR or other magnetotransport properties like Hall effect in these devices, Lake Shore cryogenic probe stations with integrated magnets are well suited (Figure 2). Three different versions of these probe stations are available. The VFTTP4 has a 2.5 T superconducting magnet with the field oriented perpendicular to the sample. The HFTTP4 is a 1 T superconducting magnet with the field oriented in the plane of the sample. In these environments, the magnetic field can be changed simply by changing the current in the magnet; the magnetic field produced by the superconducting magnet depends to a high degree of accuracy linearly on the current. The third system is the EMTP4, which uses an electromagnet to produce a 0.55 T field in the plane of the sample. This system can be used at room temperature - the magnet does not need to be cooled to produce a field. In this system the field is measured using a gaussmeter and Hall probe.

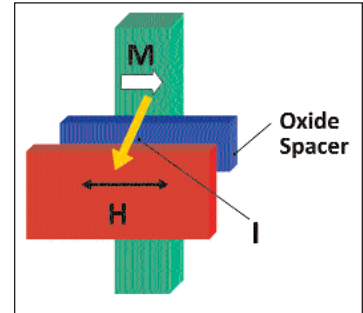


Figure 1. In a magnetic tunnel junction, the current transport is between two magnetic layers separated by an oxide insulator. The current that tunnels through the oxide is lower (resistance higher) when the magnetic fields in the layers are opposing.

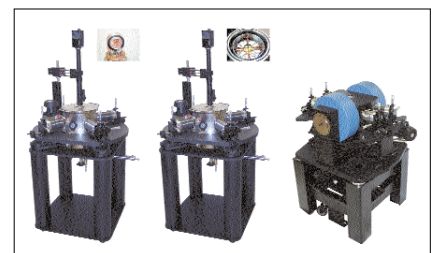


Figure 2. Model HFTTP4, Model VFTTP4, and Model EMTP4

In each of these magnet probe stations the temperature of the sample can be changed and controlled quickly and precisely, while the temperature of the superconducting magnet is kept below the transition temperature. Using moveable probes for the electrical connection has several advantages. A typical configuration for magnetic tunnel junctions (MTJ) is a stack with a top contact for each device. The bottom contact of each device is connected to the common substrate of the sample. With the field in the plane of the sample, this configuration is called current perpendicular to the plane (CPP). With a probe station, the four contacts to the sample are simply made by connecting two probes to the common substrate and two contacts to the top contact. In this configuration, current vs. voltage (IV) curves can be measured as well as the resistance vs. magnetic field. The two connections on the top contact are all that need to be moved to the next device (with a different oxide thickness, for instance). In this manner, the TMR dependence on temperature and oxide thickness can be quickly mapped out.

Instrumentation Considerations

The instrumentation package to use for the electrical measurements depends on the resistance range to be measured and the desired measurement results. There are two different ways to measure a resistance. The source can be a voltage source and the current measured. This is a direct measurement of the conductance and typically is used for higher resistance measurements. Current measurement requires several components that the experimenter selects and assembles into a measurement system. These include the instruments and components directly used in the measurement, voltage source, cable connectors, adapters, device to be tested and current meter. Other components include the environment of the device under test, the environment of the instrumentation, the measurement protocol and the topology of the connection. All of these components contribute to the quality of the current measurement. In a well-designed measurement system, it is possible to measure changes in current of less than 2 fA on samples mounted in a Lake Shore probe station.

The second method, typically used in lower resistance measurements, is to use a current source and measure the voltage. This is a direct measurement of resistance. Like the previous description, all components in the measurement are important and require attention for the best results. For a nominal resistance of 10 Ω and a measurement current of 1 mA, a well-designed measurement system will have peak-to-peak resistance noise of 0.003 Ω (0.03 percent). Figure 3 is a plot of the TMR of a MgO tunnel junction taken with this method.

An important consideration to obtain these levels of noise performance is the device temperature. When the temperature of the samples is changed, the samples will be under stress caused by temperature gradients. These stresses can develop

measurement noise by several mechanisms, such as piezoelectric effect, thermal electric effects, changes in contact resistance and movement of the sample. As the samples approach an isothermal condition, these stresses reduce, leading to a reduction of the electrical noise. It is very important to allow the samples to reach a steady state condition before making a measurement.

Hall Effect Measurements

A typical application for vertical field measurements is the Hall effect. An ideal Hall effect measurement would produce a zero Hall voltage at zero field. However, this result is valid only if the Hall voltage contacts are on the same constant potential line of the sample. In practice this is impossible to achieve. Since the Hall effect is an odd function of the magnet field, the standard method to eliminate the offset voltage is to measure the Hall voltage at positive and negative fields, and subtract the voltages to remove the offset. This is most easily done using a true bipolar power supply. The magnetic field can then be easily reversed by changing the sign of the current. Using a mechanical relay to switch the power supply magnet leads is complicated, should only be done at zero current, and contains mechanical components that are subject to failure. A second application where a true bipolar supply is an advantage is the measurement of the magnetoresistance of soft magnet materials, for instance Permalloy. In this case the field region of interest is at very low fields, close to the coercivity of the material. A true bipolar supply provides smooth and continuous control of the current through zero. This allows magnetoresistance measurement to be completed more quickly and with high precision.

In conclusion, we have seen that measurement of magneto-transport in advanced materials involves a large number of experimental parameters that must be understood and controlled.

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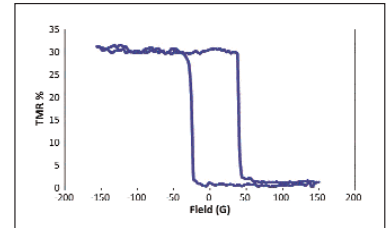


Figure 3. Tunneling Magnetoresistance Ratio of MgO Magnetic Tunnel Junction